Computer Aided Surgery for Percutaneous Nephrolithotomy: Clinical Requirement Analysis and System Design

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Abstract— **Percutaneous nephrolithotomy (PCNL) for the treatment of renal stones and other related renal diseases has proved its efficacy and has stood the test of time compared with open surgical methods and extracorporal shock wave lithotripsy. However, access to the collecting system of the kidney is not easy because the available intra-operative image modalities only provide a two dimensional view of the surgical scenario. With this lack of visual information, several punctures are often necessary which, increases the risk of renal bleeding, splanchnic, vascular or pulmonary injury, or damage to the collecting system which sometimes makes the continuation of the procedure impossible. In order to address this problem, this paper proposes a workflow for introduction of a stereotactic needle guidance system for PCNL procedures. An analysis of the imposed clinical requirements, and a instrument guidance approach to provide the physician with a more intuitive planning and visual guidance to access the collecting system of the kidney are presented.**

I. Introduction

PERCUTANEOUS nephrolithotomy (PCNL) is a surgical procedure to remove stones from the kidney through a small puncture wound through the skin after intracorporal lithotripsy. PCNL has proved its efficacy and has stood the test of time compared with open surgical methods [1] and extracorporal shock wave lithotripsy [2]. Developments in instrumentation, radiological imaging, and urologist skills have helped this type of surgery to achieve new frontiers in terms of safety and efficacy. This method has acquired a reputation of a low failure rate and has been a superior alternative to shock wave lithotripsy.

PCNL is typically performed with the patient in the standard prone position allowing a large surface area for the puncture site, less tissue along the way to the kidney, and a wide space for instrument manipulation. It has been presumed that a posterior puncture possibly minimizes the risk of splanchnic, vascular injury, hemorrhage (with a rate of 3% to 12%) and bowel injury (with a rate of 0.2% to 0.5%) [3]. The initial planning is based on a pre-operative Computer Tomography (CT) scan acquired prior to the intervention. After planning the access points to the collecting system of the kidney, the actual puncture is performed. Thereafter, a guide wire is placed through the needle and the puncture channel is dilated to place a 30 French dilatator sheath (Amplatz), so that the stone can be fragmentated and removed in pieces by minimally invasive instruments. .

The most difficult point of the procedure is the access to the collecting system of the kidney. Ultrasound (US) guided puncture provides only a two dimensional view of the surgical scene and the exact site of the puncture is sometimes very difficult to reach. Consequently, several punctures are often necessary increasing the risk of renal bleeding, injury or damage to the collecting system with subsequent perforation and inability of continuing the procedure. Moreover, the prone position also has inherent drawbacks, for example, it is risky for patients with cardiopulmonary ailments and markedly obese patients due to compression of the vena cava with concurrent reduced back flow. These problems in addition to the time spent/risk taken to turn the patient to prone position shows the benefits of puncturing sometimes in supine position. However, this requires a precise way of avoiding anatomical obstacles and a better visualization of the final aim. One way of addressing these problems is by means of stereotactic instrument guidance.

The general principles of computer navigation were described in [4] and [5], and have been applied to many different clinical areas. Among others, needle guidance applications are highlighted, in which systems have been developed to address liver puncture [6], vertebroplasty [7], [8], and general biopsy procedures [8]. All these systems are able to navigate needles; however, none of them studied the feasibility of navigation applied to renal calculi. In this field, Mozer et al. [9] present a system that relies on the registration of CT and US to provide the physician with precise needle guidance. Nevertheless, the use of US images is not always possible, e.g. obese patients, or patients in supine position with a long distance to the target.

Hence, this paper describes a workflow for introduction of

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a stereotactic needle guidance system for PCNL interventions which conforms to clinical requirements. Based on this analysis, an instrument guidance system using a standard fiducial based registration method [10] is presented. This solution aims to provide better procedure planning and more intuitive visual guidance during the access to the collecting system of the kidney.

II. MATERIALS AND METHODS

This section describes the technical and clinical requirements for a PCNL navigation system and the necessary workflow for incorporating computer navigation in this type of procedure.

A. Technical Requirement analysis

PCNL is performed in a sterile OR environment with fluoroscopy and ultrasound imaging support. The high technical complexity and the usage of different imaging devices require a navigation setup which is flexible to use and can be integrated in the existing OR environment. The working space for instrument tracking is limited to the area of surgical actions where the positions of needles and the patient need to be measured. Interaction with the navigation system and efforts for patient tracking are to be reduced to a minimum in order to avoid additional complexity in the surgical workflow.

B. Workflow Description

In order to introduce navigation in the PCNL workflow, some additional steps are necessary. For example, skin markers must be applied to the patient before the pre-operative CT scan. A detailed description of the procedural workflow is presented below:

1) **Imaging Patient Preparation:** Radio-opaque fiducial markers (Beekley PinPoint#128, Fig. 2) are placed on patient skin surrounding the approximated puncture area;
2) **Pre-operative Imaging:** A pre-operative CT image including the fiducial markers and the kidney is acquired with patient lying in the intended surgical position. After imaging, the precise location of the markers are drawn onto the skin with a marker pen and the radio-opaque markers are removed from the patient;
3) **Surgical Planning:** The planning procedure is accomplished offline prior to the intervention. The kidney and surrounding critical structures are segmented from the CT data and the access path is defined using the volumetric CT data and segmented 3D representations thereof. Paths composed of a point-pair defining the target location and the needle entry point are chosen, such that critical anatomical structures are avoided. The planned data is then saved for later use during the intervention;
4) **Patient Preparation:** Anesthesia and retrograde, transurethral insertion of a urethral catheter for filling of the collecting system in the kidney is administered with the patient in the supine position. The patient is then placed in the final surgical position, and an optical reference is attached on his skin near the marks drawn after pre-operative imaging;
5) **Needle Calibration:** The needles optical references are attached and its tip position and axis orientation are calibrated relative to the needle tracker coordinate system;
6) **Patient to Image Registration:** The patient is registered to the pre-operative image data using the fiducials in order to establish the correspondence between the surgical scenario and the planning data;
7) **Needle Guidance:** During the actual needle insertion, the physician steers the needle to the kidney using the visual feedback provided by the navigation systems graphical user interface. The needle insertion is visualized in the segmented 3D data and reformatted CT slides showing the needle insertion plane are calculated in realtime.
8) **Position validation:** During the needle insertion process, fluoroscopic images are acquired in order to validate the correctness of the needle insertion path (2D validation). The target is considered reached when the standard fluoroscopy images together with contrast agent injection ensure that the needle is inside the kidney collecting system.
9) **Stone Removal:** The inserted needle is used to prepare the path for the nephroscope. Kidney stones are broken in small pieces and removed by special graspers.

C. Navigation System

The instrument guidance system (Fig. 1) consists of an optical tracking camera (NDI Vicra camera, Northern Digital Inc., Waterloo, Canada), two touch screens and a computer which are fixed onto a transportable support. The tracking camera provides a working volume of around $0.125m^3$ which is sufficient to cover the entire working space. The use of passive optical tracking technology allows

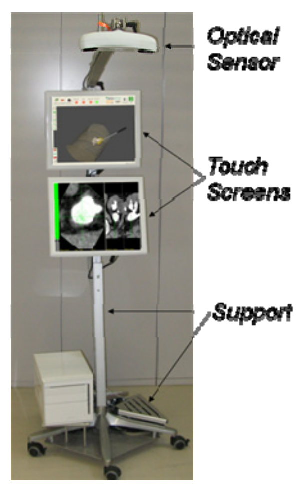

Fig. 1. Instrument guidance system.

for high flexibility in the choice of the needles and avoids additional complexity introduced by wired connections to the navigated instruments. The touch screens are packed into sterile covers and facilitate easy user interaction. The navigated instrumentation set (Fig. 2) consists of an optical needle reference, a calibration device, and an optical patient reference to be attached to the patient by means of a belt or through sterile tape.

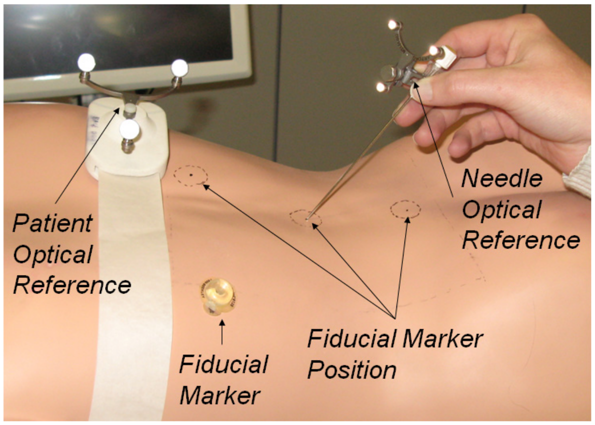

Fig. 2. Patient optical reference setup with the fiducial marker used for imaging and their respective positions marked with a surgical pen.

D. Software design and interaction concept

The system provides the following functionalities: 1) intervention planning, 2) instrument calibration 3) registration, and 4) instrument guidance.

The planning of the procedure is based on the CT datasets and can be performed prior to the surgery. This enables the use of interaction devices such as mouse and keyboard for precise localization of different insertion paths. The planned procedure can be saved, and quickly loaded to the system during the intervention.

Calibration, registration and guidance are performed intra-operatively. Therefore, within this phase, sterile components are required, and system interaction is kept minimal in order to avoid disturbing the usual surgical workflow. For this purpose, automatic detection of surgical actions is integrated into the system and allows for touch-free instrument calibration and patient registration. Once registration is confirmed, the needle guidance application is started.

E. Experiment

In order to get the physicians feedback about the developed system, an experiment with a rapid prototyped (Fig. 3) phantom was setup. Physicians were asked to interact with the system and to give their opinion about the functionalities provided. The steps required for incorporation of computer navigation in PCNL interventions were explained to them and the proposed workflow was validated to look for points incompatible with clinical routine.

III. RESULTS

A. Surgical Planning

In the planning module (Fig. 4), three standard planar views (Coronal, Sagittal, and Axial) provide the same functionality as used in clinical routine, and one 3D viewer provides an overview of the planned situation. Using the planar viewers the user can precisely set the target location,

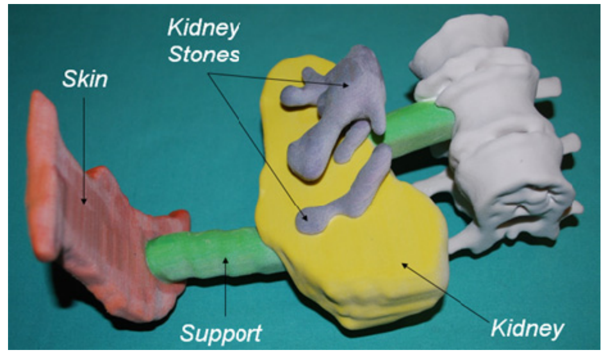

Fig. 3. Rapid prototype model used to demonstrate the system to the physicians.

and through the 3D viewer a needle entry point can be quickly chosen by selecting a position on the patient skin. These two locations define the planned trajectory that can be verified on the trajectory viewer. This viewer can be rotated around the planed path to help find possible anatomical obstacles. Additionally, the fiducial markers are defined in the CT for later registration.

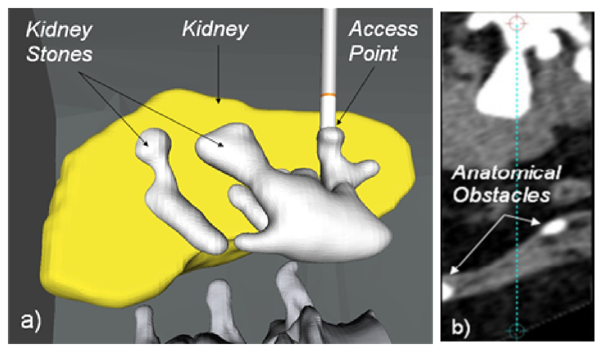

Fig. 4. a) 3D viewer showing the planned access point. b) Trajectory viewer showing the planned trajectory with possible anatomical obstacles.

B. Calibration and Registration

For calibrating the needle tip and its axis orientation, the needle is simply placed in the calibration device and displayed to the optical tracking system. The calibration process triggers automatically, as soon as the needle and the calibration unit are in their ultimate calibration configuration. To register the patient anatomy with the available imagery, the surgeon digitizes the fiducial markers using the navigated needle. A conventional pair-point matching algorithm is then applied to calculate the patient to image registration transformation. The complete process takes between 20 and 30 seconds.

C. Needle Guidance

The navigation functionality (Fig. 5) provides visual information to guide the needle to the target according to the planned trajectory. It consists of three main viewers: the 3D viewer offering an overview of the intervention scenario for needle entry point localization; the targeting viewer offering a view along the planned trajectory and looking towards the planned target, together with distance information; and, the needle plane viewer displaying a plane aligned vertically with the needle axis that is useful for obstacles detection.

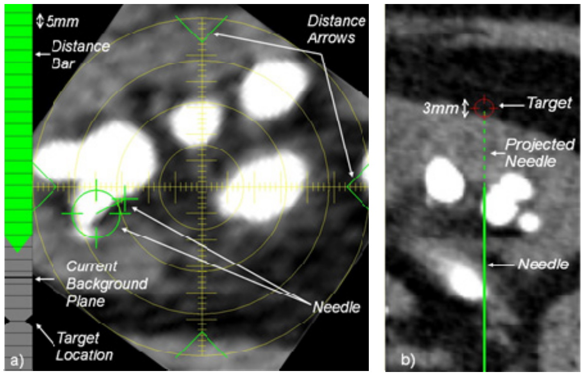

Fig. 5. a) Target viewer. b) Needle plane viewer.

IV. CONCLUSIONS AND DISCUSSIONS

This paper presents an instrument guidance system aimed at high precision percutaneous nephrolithotomy. A dedicated workflow for instrument guidance in PCNL interventions conforming to specific clinical requirements has been described. An instrument guidance system was developed to guide urologists in accessing the collecting system of the kidney. This system was then validated by clinical experts in a laboratory setup using an anatomical phantom. The complete workflow was reviewed with physicias to identify conflicts with the OR requirements and workflow specifications. The experts' feedback was positive regarding the guidance visibility and planning capability introduced by the system. Accordingly, the guidance solution not only provided spatial orientation inside the body, but also the opportunity to visualize upcoming obstacles. The proposed solution did not interfere with the current adopted clinical workflow, as the stereotactic needle guidance system was considered to be an additional tool. The only steps not actually present in the standard procedure PCNL workflow (i.e. needle calibration and patient to image registration) were not considered disturbing, as they are fast and require minimum interaction.

Although stereotactic guidance introduces a better sense of orientation when steering the needle to the target, it is known that different effects will contribute to spatial errors in the instrument guidance phase. The main sources of such error are deformations caused by needle-tissue interaction, as summarized by Abolhassani et al. in [11], and organ deformations caused by breathing, as showed in [12]. However, during the PCNL procedure the patient is intubated and consequently the respiratory cycle is well controlled allowing a gating at the same respiratory position while puncturing. The needle-tissue interaction can be controlled by teaching the physician to not correct the needle direction by bending it while inside the body. In any case, these deformations can be followed up by the intra-operative image modalities mentioned above.

The positive output of this work allowed and motivated further evaluation of the system under clinical conditions and therefore an experiment with real patient is being planned in the near future. The possibility of incorporating the intra-operative image modalities used in the standard PCNL procedure as an update of the current scenario for the navigation system is also being investigated.

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